Dissipative Dynamics of Inflation

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Abstract

Dissipative scalar quantum field theory is examined at zero temperature. Estimates of radiation production are given. Relevance of the results to supercooled and warm inflation are discussed.

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The basic picture of inflationary dynamics centers around a scalar field often called the inflaton. During the inflationary period, the potential energy of this field is pictured to dominate the energy density of the universe, thereby driving inflation-like accelerated expansion of the scale factor. The inflaton field also is required to interact with other fields, so as to allow transfer of energy from potential energy into radiation. Eventually the radiation energy density must dominate so that inflation can terminate into a standard hot big-bang radiation dominated regime. Although ultimately for inflationary dynamics to fit into a realistic particle physics scheme, the final models may be more elaborate, it is believed that these simple inflaton models contain all the essential features that must be found in any more realistic model.

The most nontrivial aspect of the inflaton models is understanding the energy transfer dynamics from potential energy to radiation. A commonly followed picture is that dissipative effects of the inflaton field can be ignored throughout the inflation period, thus leading to a supercooled inflationary regime. However, from a thermodynamic perspective, this picture appears very restrictive. The point being, even if the inflaton were to allow a minuscule fraction of the energy to be released, say one part in 10^{20}, it still would constitute a significant radiation energy density component in the universe. For example, for inflation with vacuum (i.e. potential) energy at the GUT scale $\sim 10^{15-16}$GeV, leaking one part in 10^{20} of this energy into radiation corresponds to a temperature of 10^{11}GeV, which is nonnegligible. In fact, the most relevant lower bound that cosmology places on the temperature after inflation comes from the success of hot Big-Bang nucleosynthesis, which thus requires the universe to be within the radiation dominated regime by $T \stackrel{>}{\sim} 1$GeV. This limit can be met in the above example by dissipating as little as one part in 10^{60} of the vacuum energy into radiation. Thus, from the perspective of both interacting field theory and basic notions of equipartition, it appears to be a highly tuned requirement of supercooled inflation to prohibit the inflaton from even such tiny amounts of dissipation.

These considerations have led to examining the possibility of warm inflation, an inflationary regime in which radiation also is present. Warm inflation is comprised of non-isentropic expansion in the background cosmology [1] and thermal seeds of density perturbations [2–4] (see also [5]). During warm inflation, interactions between the inflaton and other fields cause the radiation energy density to remain substantial due to its constant production from conversion of vacuum energy. This expansion regime is intrinsically different from the supercooled inflation regime, since warm inflation smoothly terminates into a subsequent radiation dominated regime, without a reheating period.

The warm inflation picture has one immediate conceptual advantage in that the dynamics is completely free of questions about quantum-to-classical transition. The scalar inflaton field is in a classical state, thus immediately justifying the application of a classical evolution equation. Also, the fluctuations of the inflaton, which induce the metric perturbations, are classical. Furthermore, warm inflation dynamics offers interesting solutions to the initial condition problem of inflation [6], as well as possibilities for generating cosmic magnetic fields [7].

However despite the conceptual clarity and despite the suggestive thermodynamic considerations, deriving this dynamics from first principles quantum field theory is nontrivial. The key reasons primarily are technical. To clarify this point, a comparison with supercooled inflationary dynamics is useful. In supercooled inflation, the process of inflation and radiation production are neatly divided into two different epochs, whereas in warm inflation dynamics, both processes occur concurrently. As such, for warm inflation dynamics there is considerable and nontrivial interplay between the equations of background inflationary expansion and quantum field theory dynamics, making it technically more difficult to solve than supercooled inflation. In effect, warm inflation solutions are of an "all-or-nothing" type in that if a solution works, it solves everything and if something fails, the whole solution becomes useless. On the other hand, supercooled inflation solutions are of a "pick-and-choose" type, in that every aspect of the problem is compartmentalized, i.e. inflation, reheating, quantum-to-classical transition, and there is little continuity amongst the different problems.

Statements have been made about the impossibility of warm inflation dynamics [8]. However the dynamical considerations leading up to these conclusions were limited in their scope, as had been noted previous to this work [9]. In particular, these works looked for high temperature warm inflation solutions, under rigid adiabatic, equilibrium conditions. Nevertheless, within this limited framework, one type of warm inflation solution was obtained [10,3], and due to the "all-or-nothing" nature mentioned above, this solutions can not be discarded as a serious contender in any more complete theory of inflation [11]. Moreover, these early works [8,9] have explicated one very important point, that warm inflation dynamics is not trivial and before it can be directly solved, several missing gaps in the knowledge of dissipative dynamics must be clarified.

As one step in this direction to fill the missing gaps, recently we studied the zero temperature dissipative dynamics of interacting scalar field systems in Minkowski spacetime [12]. This is useful to understand, since the zero temperature limit constitutes a baseline effect that will be prevalent in any general statistical state. What our results show is that for a broad range of cases, involving interaction with as few as one or two fields, dissipative regimes are found for the scalar field system. This is important for inflationary cosmology, since it suggests that dissipation may be the norm not exception for an interacting scalar field system, thus suggesting that warm inflation could be a natural dynamics once proper treatment of interactions is done.

Our analysis of dissipative dynamics starts with the general Lagrangian,

$$\mathcal{L}[\Phi,\chi_j,\bar{\psi}_k,\psi_k] = \frac{1}{2}(\partial_\mu\Phi)^2 - \frac{m_\phi^2}{2}\Phi^2 - \frac{\lambda}{4!}\Phi^4 + \sum_{j=1}^{N_\chi}\left\{\frac{1}{2}(\partial_\mu\chi_j)^2 - \frac{m_{\chi_j}^2}{2}\chi_j^2 - \frac{f_j}{4!}\chi_j^4 - \frac{g_j^2}{2}\Phi^2\chi_j^2\right\}$$
$$+ \sum_{k=1}^{N_\psi}\bar{\psi}_k\left[i\,\partial\!\!\!/ - m_{\psi_k} - h_{k,\phi}\Phi - \sum_{j=1}^{N_\chi}h_{kj,\chi}\chi_j\right]\psi_k\ , \tag{1}$$

with $\Phi \equiv \varphi + \phi$ such that $\langle\Phi\rangle = \varphi$. Our aim is to obtain the effective equation of motion for $\varphi(t)$ and from that determine the energy dissipated from the $\varphi(t)$ system into radiation.

Using the tadpole method [13], which requires $\langle\phi\rangle = 0$, the effective equation of motion for $\varphi(t)$ emerges

$$\ddot{\varphi}(t) + m_\phi^2\varphi(t) + \frac{\lambda}{6}\varphi^3(t) + \frac{\lambda}{2}\varphi(t)\langle\phi^2\rangle + \frac{\lambda}{6}\langle\phi^3\rangle + \sum_{k=1}^{N_\psi}h_k\langle\bar{\psi}_k\psi_k\rangle = 0\ . \tag{2}$$

The field expectation values in this equation are obtained by solving the coupled set of field equations. In our calculation, we have evaluated them in a perturbative expansion using dressed Green's functions [12,14,9]. One general feature of these expectation values is they will depend of the causal history of $\varphi(t)$, so that Eq. (2) is a temporally nonlocal equation of motion for $\varphi(t)$.

Formally, we can examine Eq. (2) within a Markovian-adiabatic approximation, in which the equation of motion is local in time and the motion of $\varphi(t)$ is slow. At $T=0$, such an approximation is not rigorously valid. Nevertheless, this approximation allows understanding the magnitude of dissipative effects. Furthermore, we have shown in [12] that the nonlocal effects tend to filter only increasingly higher frequency components of $\varphi(t)$ from nonlocal effects increasingly further back in time. Thus for low frequency components of $\varphi(t)$, memory only is retained to some short interval in the past. Since within the adiabatic approximation, $\varphi(t)$ only has low frequency components, we believe the Markovian-adiabatic approximation is legitimate at least for order of magnitude estimates. Within this approximation, the effective equation of motion for $\varphi(t)$ has the general form

$$\ddot{\varphi}(t) + m_\phi^2\, \varphi(t) + \frac{\lambda}{6}\varphi^3(t) + \eta(\varphi)\dot{\varphi}(t) = 0\ , \tag{3}$$

where explicit expressions for the dissipative coefficient η for various cases are given in [12].

Based on this equation, energy production will be estimated here with full details given in [12]. Our primary interest is in the overdamped regime

$$m^2(\phi) = m_\phi^2 + \lambda\varphi^2/2 < \eta^2, \tag{4}$$

since this is the regime ultimately of interest to warm inflation. In this regime, the energy dissipated by the scalar field goes into radiation energy density ρ_r at the rate

$$\dot{\rho}_r = -\frac{dE_\phi}{dt} = \eta(\varphi)\dot{\varphi}^2. \tag{5}$$

In [12] we have determined radiation production for two cases

$$\begin{aligned} &(\mathrm{a}).\ m(\varphi) > m_\chi > 2m_\psi \\ &(\mathrm{b}).\ m_\chi > 2m_\psi > m(\varphi). \end{aligned} \tag{6}$$

To focus on a case typical for inflation, suppose the potential energy is at the GUT scale $V(\varphi)^{1/4} \sim 10^{15}$GeV and we consider the other parameters in a regime consistent with the e-fold and density fluctuation requirements of inflation. Note, although this is a flat nonexpanding spacetime analysis, since the dissipative effects will be at subhorizon scale, one expects these estimates to give a reasonable idea of what to expect from a similar calculation done in expanding spacetime. Expressing the radiation in terms of a temperature scale as $T \sim \rho_r^{1/4}$, we find for case (a) $1\mathrm{GeV} < T < 10^7\mathrm{GeV} < H$ and for case (b) $T \gtrsim 10^{14}\mathrm{GeV} > H$, where $H = \sqrt{8\pi V/(3m_p^2)}$.

It should be clarified that the results found in this paper in no way require supersymmetry, although they easily could be applied in SUSY models. For such models, the low T warm inflation solutions suggested by case (a) could be useful in avoiding gravitino overproduction [15]. On the other hand, case (b) in general seems more interesting, since it offers a very robust possibility for radiation production. Although this is what the formal calculation indicates, we believe at this point a deeper understanding of radiation production is necessary.

In regards the potential implications of the results discussed in this talk to inflationary cosmology, we infer that under generic circumstances the scalar inflaton field will dissipate a nonnegligible amount of radiation during inflation. In particular, the lower bound suggested by the above estimates already are sufficiently high to preclude a mandatory requirement for a reheating period. Moreover, the high temperature results of case (b) suggest that warm inflation could be very robust. Verification of these expectations requires a proper extension of these calculations to expanding spacetime, and within a nonequilibrium formulation [16], which we plan to examine.

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